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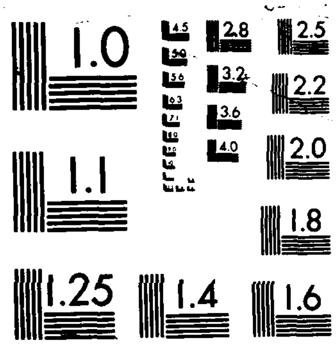

CROCOPY RESOLUTION TEST CHART

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CR 87.002
October 1986
An Investigation Conducted By
The Danish Hydraulic Institute
Sponsored By Naval Facilities
Engineering Command

NCEL
Contract Report

AD-A175 332

INVESTIGATIONS AND TESTS TO DETERMINE HYDRODYNAMIC FORCES AND MOMENTS ON SHIPS MOORED IN A CURRENT - VOL II PHASE I REPORT

ABSTRACT Experiments with 1:50-scale models produced data on the horizontal force and the yawing moment exerted by a steady current on ships moored in shallow water. Data were obtained for one ship with various headings and for two ships arranged side by side in a beam current. The models were restrained by elastic lines simulating real moorings; for a single ship, rigid supports were also used. The experiments included brief investigations of the minimum flume width, turbulence, flow patterns, and flow-induced motions.

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

METRIC CONVERSION FACTORS

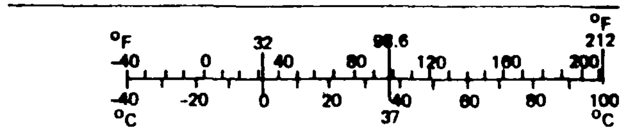
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ships, currents, shallow water, mooring; loads (forces); motion, model tests.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experiments with 1:50-scale models produced data on the horizontal force and the yawing moment exerted by a steady current on ships moored in shallow water. Data were obtained for one ship with various headings and for two ships arranged side by side in a beam current. The models were restrained by elastic lines simulating real moorings; for a single ship, rigid

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supports were also used The experiments included brief investigations of the minimum flume width, turbulence, flow patterns, and flow-induced motions. Keywords:
Ship models; Water currents,

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1. INTRODUCTION

This report describes the results of the work carried out by Danish Hydraulic Institute (DHI) under Contract No. N62474-84-C-3142 for the Naval Civil Engineering Laboratory (NCEL), Department of the Navy, Port Hueneme, U.S.A. The Danish Maritime Institute (DMI) has acted as consultants to DHI during the project.

The scope of work has covered the influence on the drag force on a ship moored in a beam current in shallow water from

- o Blockage effects
- o Reynolds number

Furthermore, the possibility of having instability type of motions was investigated. During the course of the project NCEL has been kept informed about the progress of the work.

2. SUMMARY

A limited model test programme has been conducted in order to establish the necessary flume width for measuring lateral drag forces increased by less than 5% due to blocking, as no blockage correction formulas for the three-dimensional flow exists. The application of two-dimensional correction formulas indicate a very conservative estimate of a flume width 9 times L_{pp}. The model tests have shown that for a flume width, B, of 5 times L_{pp}, lateral drag forces are not affected significantly by blockage.

The influence of Reynolds number on drag forces is well-known for various bluff bodies. The drag force is a form drag with insignificant contribution from shear stresses. For circular cylinders the drag coefficient varies significantly with the Reynolds number, with a subcritical value of C_D equal to 1.2 and a postcritial value of 0.7, approximately, for absolutely smooth cylinders. For cylinders with a rough surface the postcritical value of C_D increases, approaching the subcritical value. For bluff bodies with cross-sections having more sharp edged corners - such as squares or rectangles - the drag coefficient varies insignificantly with the Reynolds number, as the separation is fixed to the sharp corners.

The shape of a ship hull with bilge keels has similarities with both of these types of bluff bodies. The influence of the Reynolds number is thus a priori expected to be much less than for a smooth circular cylinder, and especially the difference in the C_D-values for the sub- and postcritical Reynolds number is expected to be substantially smaller. However, comparisons are extremely difficult to make as data for the high Reynolds numbers cannot be obtained in laboratory facilities, when Froude numbers and draft ratios are to be reproduced correctly as well.

Postcritical C_D-values can be obtained for smooth circular cylinders at subcritical Reynolds numbers by applying trip wires on the cylinder surface. The present model tests have revealed that stable force coefficients are obtained on a 1:50 scale model of a ship equipped with bilge keels and trip wires for the range of Froude and Reynolds numbers tested. The C_D-value was found to increase for a 1:25 scale model. This increase may be related to the decrease in turbulence level of the ambient flow for the tests with the 1:25 scale model. Another and more important observation was made during testing. When the ship was free to roll, pitch and heave the drag force increased by as much as 40% compared to the value found when the ship was restrained at the still water drafts, with zero heel. The increase is due to the heel and sinkage of the ship caused by the pressures acting on the ship hull. This observation may be part of the reason for the substantial scatter in C_D-values reported in the literature. Furthermore, the effect has obviously important consequences for the design of the mooring system.

Finally, tests have been conducted to investigate if instability motions of a violent character would occur within the range of Froude numbers from 0.08 to 0.16. No severe motions that could lead to capsizing or grounding of the ship were observed. However, the static heel and sinkage of the ship increased with increasing Froude number. Superimposed on these average movements were high frequency heave, roll and pitch motions. During testing it was noticed that the roll motion initiated the pitch and heave motions. Furthermore, it was observed that a certain heel was necessary to have sustained roll motions.

3. SCOPE OF WORK

The model study was planned in accordance with the description of work for Phase I of "Investigations and Tests to Determine Hydrodynamic Forces and Moments on Adjacent Ships Moored in a Current". Phase I covers:

- Preliminary tests to define the range of applicability of main tests.

- The phase I tests shall be short yet valid quick-look investigations aimed at getting critical guideline data.

For the floating body (a ship model or an adjusted horizontal cylinder) the following investigations were to be made:

- o Find the maximum flume width at which the lateral force on the transversely mounted vessel is not affected by more than approximately 5% relative to the situation with an infinitely wide flume.

- o Determine the influence of the Reynolds number on the lateral drag force on the hull shaped body in a beam current so that the Phase II measurements can be properly converted to full scale predictions on drag forces and moments.

- o Investigate the behaviour of a floating body when it is moored in a beam current and the speed of the current is increased. Specifically determine if and when erratic or violent motions take place.

For the specified types of investigation, Statement of Work, Ref. 1, specifically describes the environmental conditions under which the tests have to be carried out.

4. MODEL SET-UP AND INSTRUMENTATION

4.1 Model Basin

The set-up was made in a rectangular tank with the dimensions 25 m x 35 m where the inlet and outlet weirs were located along the short sides. Positions for movable walls applied in the blockage tests were marked on the horizontal floor of the tank as indicated in Fig. No. 4.1 showing the location of the walls and the vessels relative to the tank.

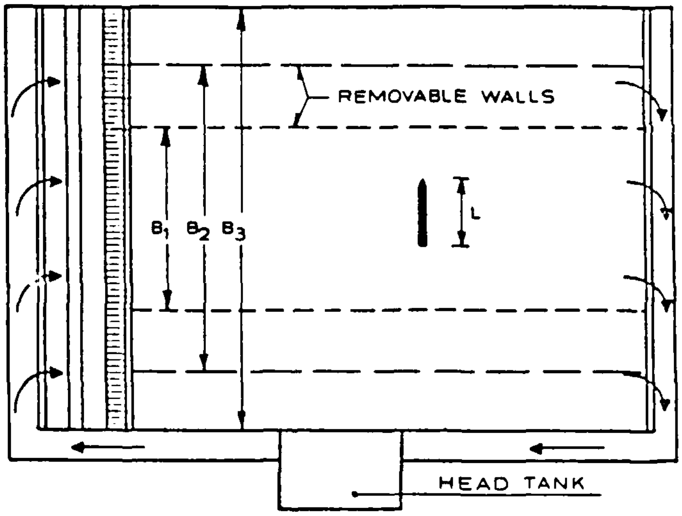


Fig. 4.1 The Position of the Vessel and the Movable Walls in the Basin.

The flow through the tank was established by use of a pump- and head tank system in connection with inlet-outlet flumes around the tank. The principle for the system operation is shown in Fig. 4.2.

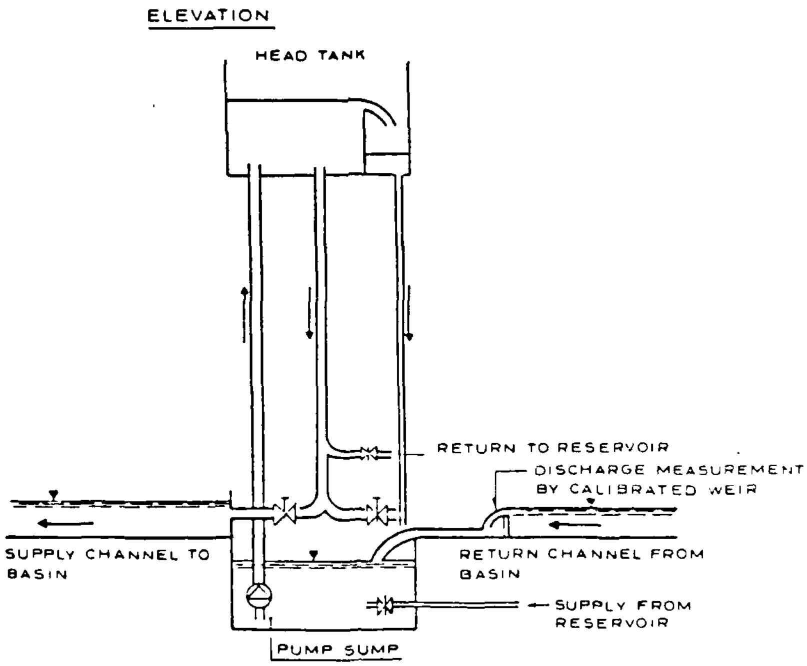


Fig. 4.2 The Principle for the Current Generating System.

4.2 Current Calibration

For each of the specified current situations the calibration procedure was as described below.

The predetermined water level was established. A current meter was mounted in the center of the flume upstream to the vessel position at a depth corresponding to 4.25 m below the surface. Preliminary investigations have shown that the velocity in this level corresponds to the average velocity over the draft of the vessel. Further, the preliminary measurements had shown that in this level the velocity, V_{draft}, was 9.2% greater than the average velocity of the flume, i.e. $V_{draft} = 1.092 \cdot V_{flume}$.

When a reasonable current velocity was established along the axis of the flume, measurements on the horizontal distribution of the current were made. Velocity measurements were taken each 0.5 m

across the flume in the level mentioned above. The horizontal distribution of the current was then adjusted by lowering or elevating the outlet weirs. When the uniform horizontal distribution was established the vertical velocity profile upstream was measured for control.

In order to determine the roughness regime for the model flow a generalized Colebrooks and Whites formula has been adopted for the description of the model flow. A high degree of correlation has been found using the following physical parameters:

$k = 0.001$ m	Bottom roughess.
$\delta = 0.002$ m	Boundary layer thickness. (Dependent on the average velocity).
$\mathbb{R} = 30 \cdot 10^3$	Reynolds Number based on the depth.
$V = 0.13$ m/s	Average velocity (3 ft/sec. (prototype).

The calculated as well as the measured velocity profile are shown in Fig. 4.3. The agreement between the two is good.

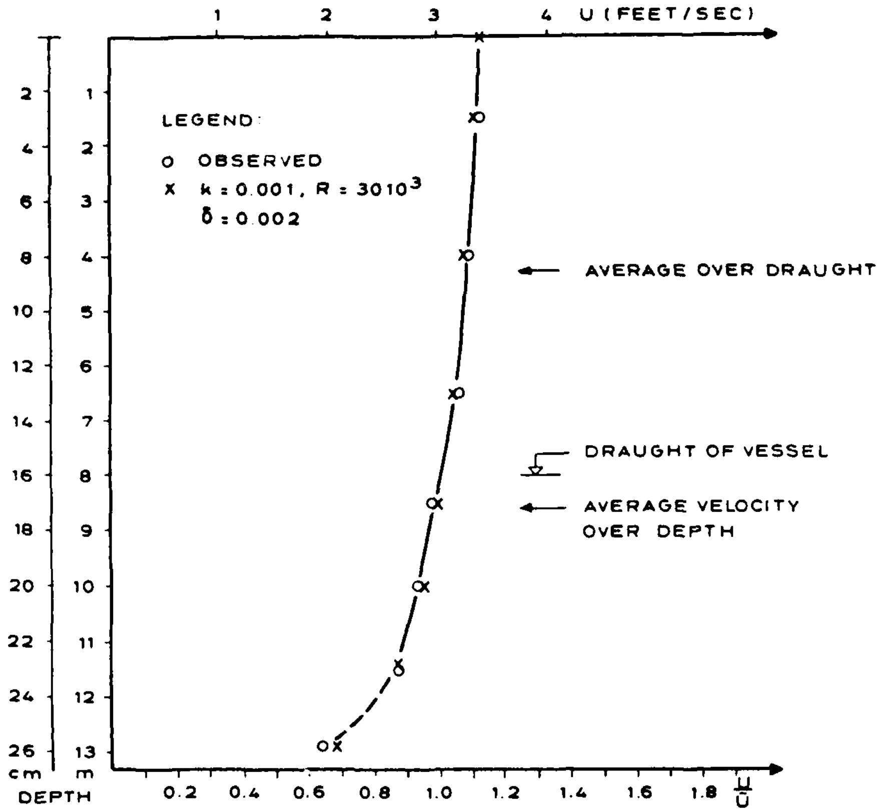
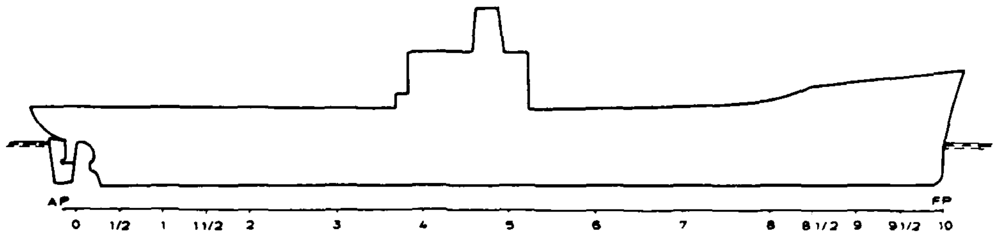


Fig. 4.3 Measured and Calculated Velocity Profile.

4.3 Vessels

The two ships used in this study were scale models (1:50 and 1:25) of the same prototype ship with the principal dimensions as outlined in Table 4.1. The body lines of the vessel are shown in Fig. 4.4.



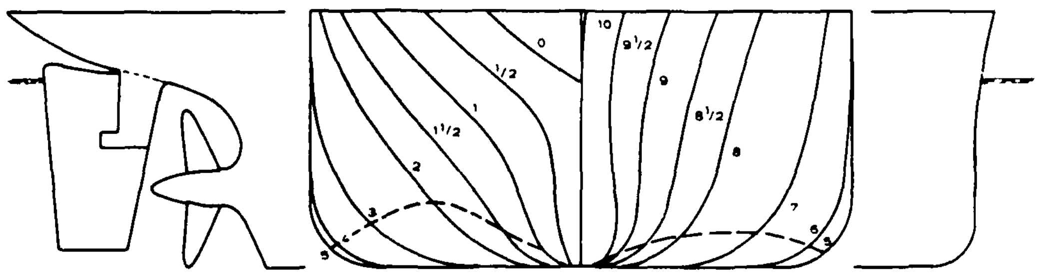


Fig. 4.4 Body lines of the ship applied in the model tests. Position of tripwires is indicated by the dotted line --.

Dimension	Prototype	1:50	1:25
Lpp (m)	160.90	3.218	6.437
T (m)	8.0	0.160	0.320
Δ (m^3)	18541	0.144	1.154
Bm (m)	23.0	0.460	0.920
Bilge radius (m)	3.05	0.061	0.122
Heights of decks (m above base line)			
Main at FP	16.764	0.335	0.671
Main at AP	15.24	0.305	0.610
Main at mid	13.716	0.274	0.549
Second at FP	12.497	0.250	0.500
Second at AP	12.802	0.256	0.512
GM (m)	2.134	0.043	-
		Ballasted to 0-trim	

Table 4.1 Dimensions for Vessels. L_{pp}: length between perpendiculars. T: draft of vessel. Δ: Displacement. Bm: moulded breadth. FP: fore perpendicular. AP: aft perpendicular. GM: transverse metacenter height.

During the tests (excluding some Reynolds number tests) the model ship was equipped with bilge keels. The height of the keels corresponded to 0.45 m and covered the central 66.0 m of the vessel. The vessels were tested with rudder and propeller.

During some Reynolds' number tests the models were equipped with trip-wires in order to stimulate turbulence in the boundary layer flow. These wires extended from the ends of the bilge keels to the perpendiculars. The precise locations of the trip wires can be seen from Fig. No. 4.4. The diameter of these wires corresponds to $8 \cdot 10^{-3}$ times the bilge radius which should trig the turbulence most efficiently according to Ref. 3.

4.4 Moorings

The moorings were simulated by stiff rods irrespective that natural moorings are elastic. The large stiffness of the mooring rods is also responsible for large fluctuations in the mooring forces as the energy absorption of the stiff moorings is minimum.

In addition, the horizontal movements, surge, sway and yaw were prevented by the use of stiff mooring rods.

The model moorings were anchored on the main deck at the axis of the ship at both perpendiculars. The heights above the keel level are given in Table 4.1.

Mooring Points

Anchored barges were simulated by fixed anchoring points 100 m upstream of the vessel. The anchoring points were elevated corresponding to 1.5 m above the water level giving the moorings an inclination of approximately 2.5 degrees.

At the fixed mooring points and at the vessel the moorings were allowed to rotate by use of spherical bearings. Thereby the action of moments caused by the single moorings was prevented.

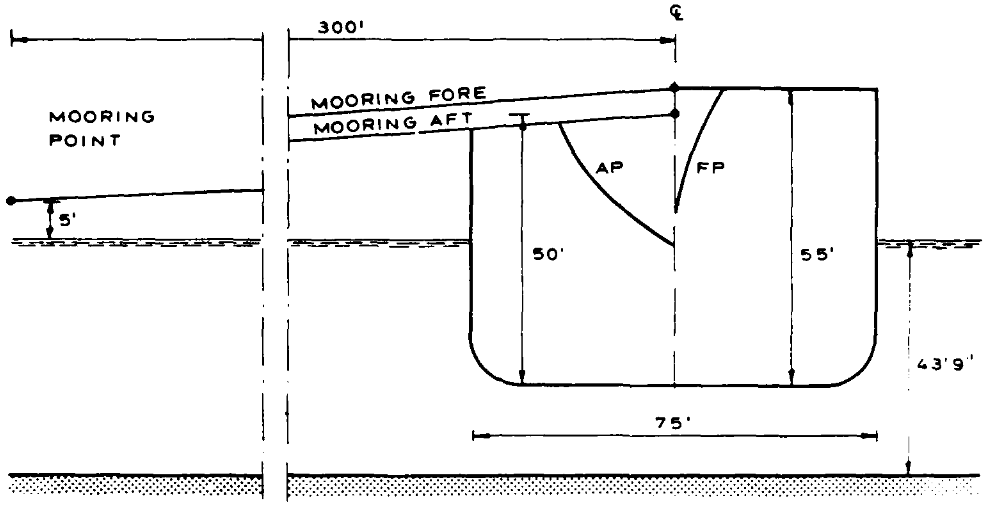


Fig. 4.5 Mooring Configuration.

4.5 Vessel Suspension

In order to measure the effects of pure blocking and to study changes in forces due to changes in the Reynolds number the vessels were suspended from thin wires during these tests keeping the bottom of the vessels horizontal. The drag forces would therefore not be influenced by reduction of the underkeel clearance otherwise appearing during heave, roll and pitch movements.

On the other hand the differences in the flow around the bow and the stern may introduce vertical movements, and these may become larger in a narrow flume. The blocking effects can therefore not be separated from natural effects in an infinitely wide flume. Thus, the suspension chosen is a compromise in order to investigate the effects due to pure blocking of the flume.

During the instability tests the vessel was floating and thus allowed to have the vertical motions, whereas the horizontal motions were prevented by the rigid mooring arrangement.

4.6 Measuring Techniques

Current

The current was measured by means of either a bi-directional ultrasonic current meter giving the instantaneous speed continuously or by a propeller current meter. The output from the former device is an analogue electrical voltage proportional to the velocity and from the latter a number on a counter preset to a certain measuring period.

During the instability tests and the Reynolds' Number tests, the current speed was measured indirectly by means of a circular plate mounted on a force transducer. The drag coefficient on a circular plate is independant of the Reynolds Number. The theoretical value of the drag coefficient is 1.19, a value that has been verified experimentally in a number of studies.

The current force acting on the circular plate has been used as a reference during the instability tests. The plate was mounted upstream of the vessels in a depth corresponding to the level of the forces acting on the vessels.

Mooring Forces

The mooring rods were fastened to force transducers consisting of a beam equipped with a pair of strain gauges. The output is a voltage proportional to the deformation of the beam and thereby proportional to the acting force.

Water Level

Resistance type wave gauges consisting of two parallel rods were used to determine the position of the water level in the flume during testing. In addition to this, a mechanical point gauge was used as reference.

Movements

The vertical movements of the (floating) vessel were measured by angular potentiometers at the bow and mid ship starboard and port side.

The pure motions heave, roll and pitch are easily derived by use of summation/subtraction amplifiers.

Data Analysis

The electrical signals from the various gauges are fed into a 32-channel microcomputer for online analysis. This analysis gave as result for each channel:

- the absolute maximum
- the absolute minimum
- the average value
- the root mean square value

for the total time series and for five subseries.

Selected time series were continuously recorded on a 12-channel UV-recorder. From these records it was possible to obtain an overall impression of the behaviour of the forces acting on the moored vessel and its motions.

During the instability tests the time series of the motions and of the forces were recorded on a 7-channel analogue tape recorder. These signals were later digitized and stored on a microcomputer making it possible to produce plots of the time series of the pure motions and of the resultant forces.

Estimated Inaccuracies

Table 4.2 below outlines the various sources of inaccuracies and their estimated contributions of the uncertainties of the total force (or force coefficient).

Item	Absolute	Contribution to calculated C_D
Vessel		
Length	1 mm	$3 \cdot 10^{-4}$
Draft (ballasting)	1.5 mm	$9 \cdot 10^{-3}$
Water		
Depth	1.5 mm	$6 \cdot 10^{-3}$
Average current speed	5 mm/s	$8 \cdot 10^{-2}$
Level of turbulence (uncontrolable)		$5 \cdot 10^{-2}$
Equipment		
Current meter	~ 5 mm/s	$8 \cdot 10^{-2}$
Force Transducer	5 grammes/kg	$5 \cdot 10^{-3}$
Total relative standard deviation on force coefficients		$8 \cdot 10^{-2}$

Notation

The lateral drag force coefficient for the models has been determined as:

$$C_D = F_y/(\tfrac{1}{2}\ \rho\ L_{pp} \cdot T \cdot V^2)$$

where C_D is the lateral drag force coefficient, F_y the total lateral force, i.e. the sum of the forces measured fore and aft. ρ is the water density, L_{pp} the length between perpendiculars and T the draft. V is the velocity measured at a depth corresponding to 0.53 times the draft. This velocity deviates insignificantly from the velocity averaged over the draft of the ship. The current meter was mounted at this depth during the tests.

5. BLOCKING TESTS

5.1 Problem Assessment

It is a well known fact that the forces experienced by structures placed in a confined flow are larger than those in an infinite flow area. The phenomenon has mainly been studied for 2-dimensional flow around cylindrical structures, for which analytical or semi-empirical correction formulas have been proposed. The drag on a cylinder in confined flow may be found from the expression:

$$C_D = C_{DM} \cdot \left(1 + \frac{\pi^2}{12} \cdot \varepsilon^2 + \frac{1}{4}\,\varepsilon\, C_{DM}\right)^{-2} \qquad (5.1)$$

where ε is the blockage ratio, C_{DM} the measured drag coefficient and C_D the corrected value of this.

For a floating ship in shallow waters exposed to a beam current the flow field is much more complicated and no correction formulas are readily available. Applying the above Equation (5.1) indicates that for a C_{DM} value of 1.5 and a correction being less than 5%, the value of ε should be less than 1/15, i.e. for a draft ratio of 0.6 the width of the flume should be 9 times the length of the ship. However, a major part of the flow passes underneath the vessel, and hence a much narrower flume is expected to give values within 5% difference from the infinite area case.

5.2 Model Tests

The blocking tests were carried out using the 1:50 model ship. The range of flume width to the ship length ratio was varied from 1.5 through 2.0, 3.0, 3.5, 4.0 to 7.8 with the Froude number 0.08 in order to establish a reference case. For the Froude numbers of 0.12 and 0.16 tests were made with two blockage ratios of 3.0 and

4.0. All tests were conducted with a draft to depth ratio of 0.6.

It was observed that a floating ship heeled several degrees at the Froude number of 0.08, for which reason the vessel was kept fixed in the vertical direction in order to prevent the roll, heave and pitch motions as described in Section 4. It was also observed during the testing that the floating and heeling ship experienced larger transverse forces than the fixed ship. Further discussion of this is given in Section 6.

5.3 Test Results

The resulting drag coefficients for the situation with $\mathbb{F}$ = 0.08 are given in the table below. The values are average values over 25 min. test time corresponding to approximately 3 hours in nature.

B/L	$\bar{V}$ (m/s) (Prototype)	C_D
1.5	0.788	2.44
2.0	0.846	1.71
3.0	0.754	1.61
3.5	0.780	1.51
3.5	0.803	1.48
4.0	0.745	1.64
7.8	0.791	1.32

Table 5.1 Drag Coefficients, $\mathbb{F}$ = 0.08. Vertically Fixed Ship.

Tests were made with Froude numbers 0.12 and 0.16 at the two flume widths B/L ~ 3.0 and 4.0. Table 5.2 below summarizes the results with respect to drag coefficients.

B/L	$\bar{V}$ (m/s)	C_D
3.0	1.46	1.70
3.0	1.28	1.84
4.0	1.37	1.57
4.0	1.36	1.58
3.0	1.71	1.67
3.0	1.73	1.65
4.0	1.76	1.49
4.0	1.75	1.55

Table 5.2 Drag Coefficients, $\mathbb{F} \sim 0.12$ and 0.16.

The effect of the flume width on the lateral drag coefficient is quite clear from the figures given in the tables above.

5.4 Discussion of Results

The drag coefficients found in the model tests are shown in Fig. 5.1 below. Apart from the C_D-value for $\mathbb{F} = 0.08$ and $B/L = 4$ the variation of C_D with the B/L-value is rather consistent. Taking the C_D-value found for $B/L = 7.8$ as applicable for the infinite wide flume case it appears that a flume width of 4 to 5 times the length of the ship will yield lateral drag coefficients that differ less than 5 per cent from the infinite flume case.

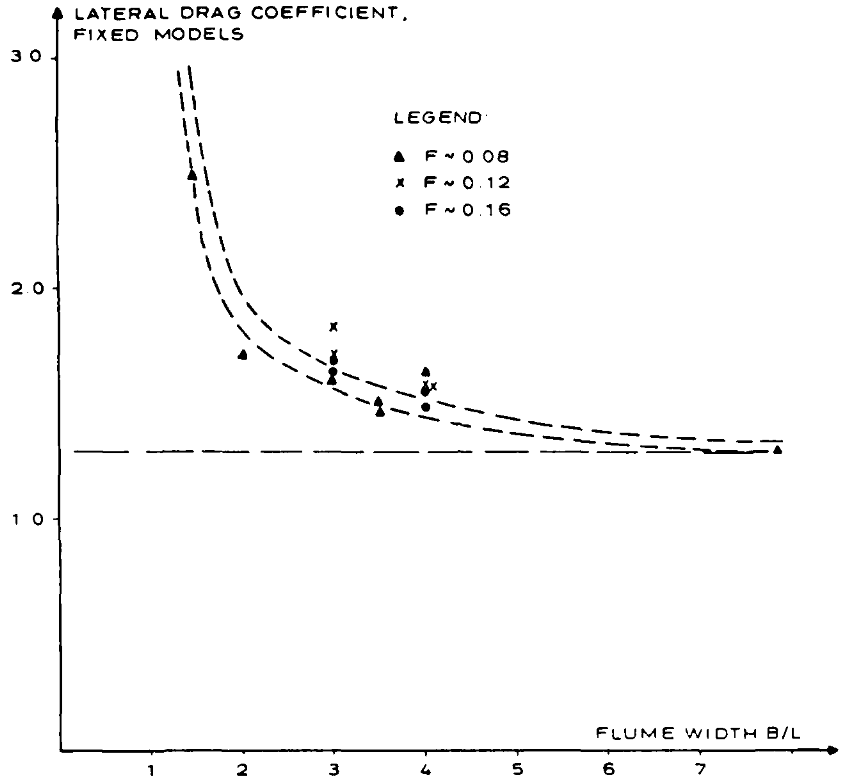


Fig. 5.1 C_D-Values vs. Blockage Ratio, B/L, for 3 F-Values.

The lateral drag coefficient as recommended by OCIMF, Ref. /1/, is shown versus the depth to draft ratio in Fig. 5.2. As indicated in the figure a somewhat larger C_D-value is given by OCIMF for H/D = 1.67 than found in the present study. No information is given in Ref. /1/ with respect to blockage ratio in the model tests or Froude number, but the Reynolds number was of the order of 10^5 and it seems likely that the ship has been held fixed in vertical position as for the present investigations.

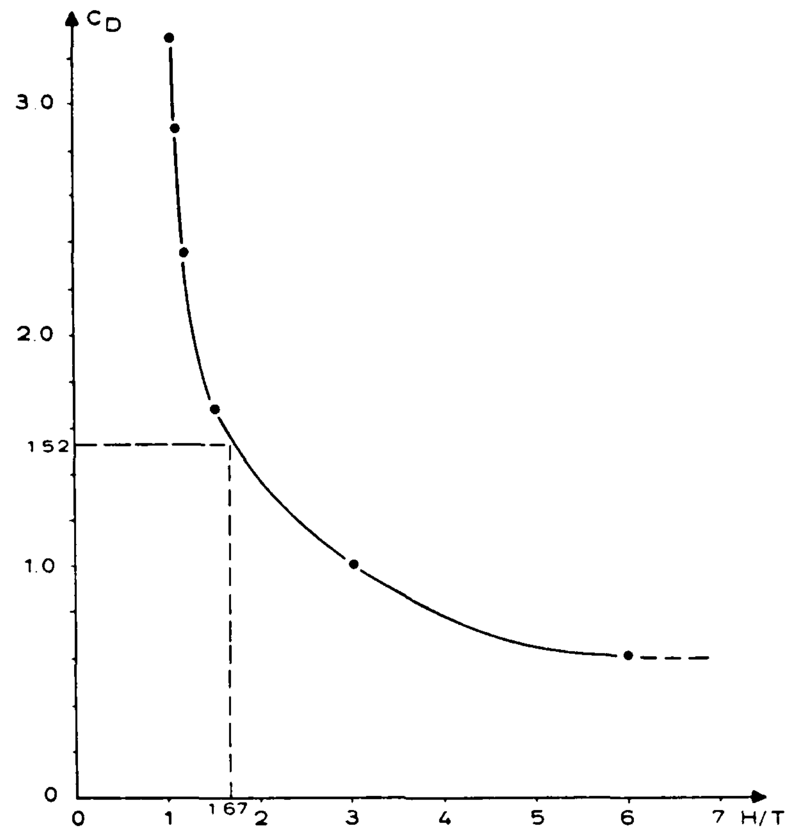


Fig. 5.2 Lateral Drag Coefficients, C_D, on a VLCC as Recommended by OCIMF for Various Depth/Draft Ratios, H/T.

The discrepancy between the OCIMF and the present data is, however, not surprising considering that different types of ships were modelled and different facilities applied. The reported data in literature show a large scatter in lateral drag coefficients, as illustrated by the data compiled by NCEL, Ref. /2/, and reproduced in Fig. 5.3.

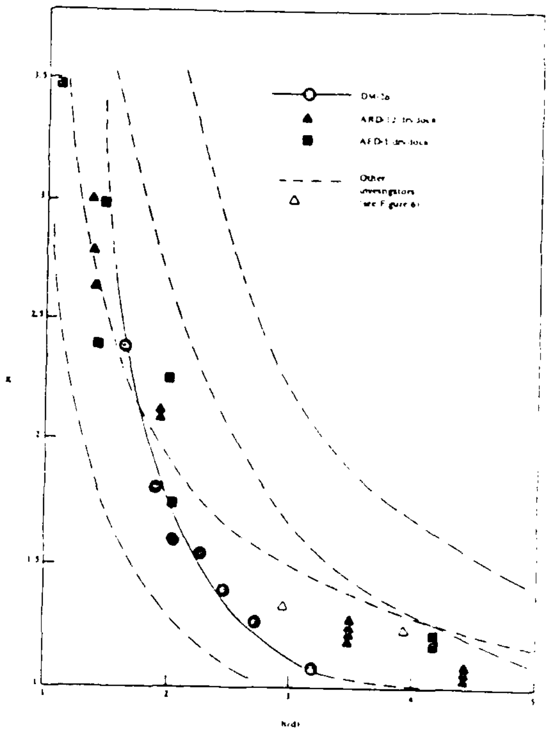


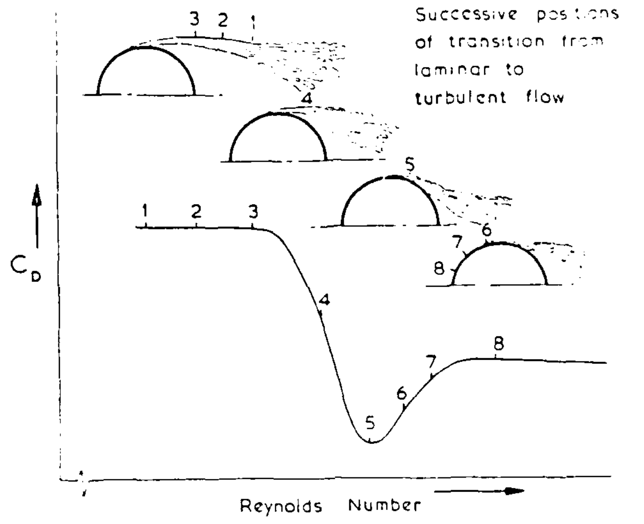
Fig. 5.3 Relative Drag Coefficients vs. the Depth/Draft Ratio. From Ref. /2/.

6. REYNOLDS NUMBER EFFECTS

6.1 Assessment of the Problem

As for the blockage phenomenon, the effect of Reynols number on fluid drag forces on bluff bodies has mainly been studied for 2-dimensional flow around cylindrical structures. The well-known variation of C_D for a circular cylinder is shown in Fig. 6.1 below together with sketches of the boundary layer and separation characteristics. As seen from Fig. 6.1 the value of C_D is closely connected to the characteristics of the boundary layer and the position of the separation point. Other phenomena that affect the C_D-value and its variation with the Reynolds number are surface roughness and turbulence in the oncoming flow. For cylinders in close proximity to a rigid boundary, the drag coefficient is affected by the magnitude of the gap between the cylinder and the boundary. Furthermore, the boundary layer developing along the fixed boundary influences the forces on the cylinder.

Extensive model test programmes have been conducted to investigate the possibilities of reproducing high Reynolds number forces on cylinders at lower Re-values by some artificial means. The use of roughness or trip wires to stimulate the development of turbulent boundary layers is the most frequently applied methods. Ref. /3/ summarizes the results of a recent investigation on this phenomenon, and it is concluded that the use of trip wires and Re $\sim 10^5$ yielded forces and vortex shedding frequencies comparative to those for smooth cylinders at high Reynolds number ($\sim 10^7$). The results are reproduced in Fig. 6.2, where the C_D-values and Strouhal numbers, S, are given.



CHANGES FROM SUBCRITICAL (1,2,3) TO POSTCRITICAL (8) FLOW; NATURAL SEQUENCE OF CHANGES FOR A SMOOTH CYLINDER (DIAGRAMMATIC)

Fig. 6.1 C_D vs. the Reynolds Number together with Sketches of the Flow and the Boundary Layer. Ref. /3/.

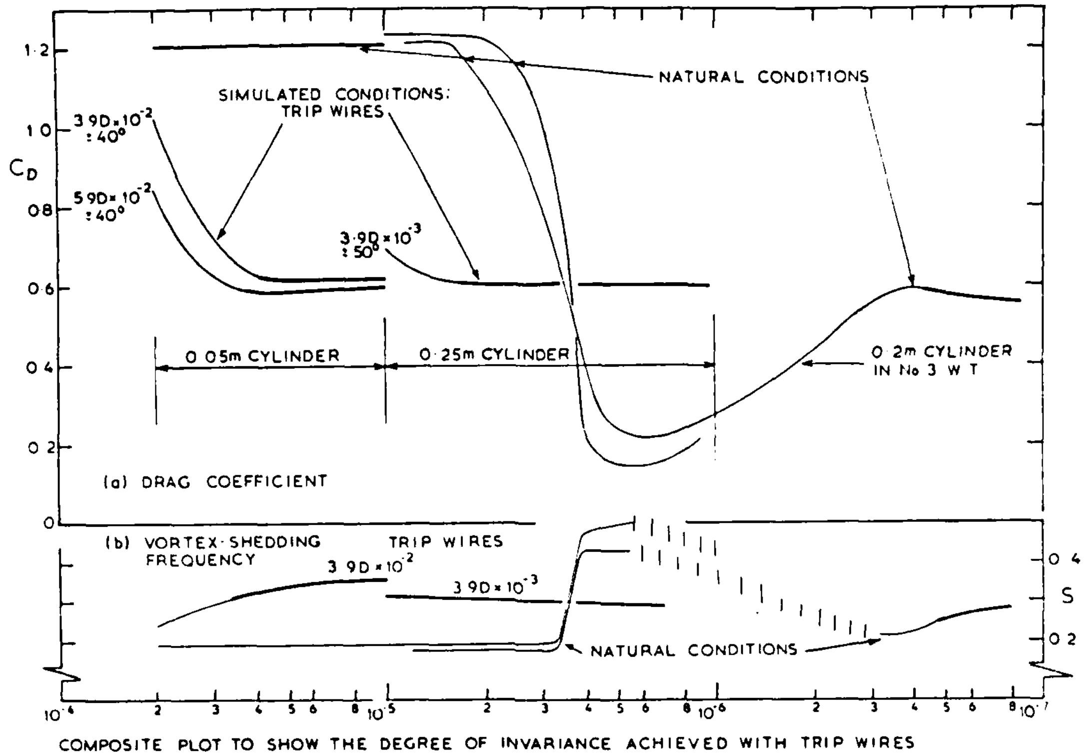


Fig. 6.2 Effect of Trip Wires on Drag Coefficient, C_D, and Strouhal Number, S. From Ref. /3/.

For bodies with more sharp-edged corners the drag coefficient becomes more constant and for plates C_D is in fact invariant for Reynolds numbers above 10^3.

A ship hull fitted with bilge keels has features which resembles both the circular cylinder and a more sharp-edged body, meaning that the Reynolds number effects a priori are expected to be less significant than for the circular cylinder.

It is important to note that for flow around ships the Froude number may have significant influence on the force. Therefore the Reynolds number effects cannot be investigated just by increasing the velocity as this also increases the Froude number. Only by using two different models at different scales the influence of

Reynolds numbers can be investigted for otherwise identical conditions.

6.2 Model Tests

The existence of possible Reynolds number effects on the lateral current force acting on model ships has been investigated through a test series. Two different scale models of the same prototype ship have been used for this purpose. The two models (of scale 1:25 and 1:50) have been exposed to beam current of approximately identical Froude numbers but different Reynolds numbers. In both situations the models were in vertically fixed positions and the lateral drag coefficients have been determined and compared.

In order to obtain an accurate comparison between the forces on the two ships, the force excerted on a circular plate was used as reference. The plate was placed at a certain relative depth below the surface and distance upstream the ships.

The key figures from the tests are then the ratio between the current force per unit area on the vessel and on the circular plate.

The flume width for these tests was chosen as small as 2 times Lpp making it possible to obtain a reasonable Froude number for the large scale model (1:25). Although this B/Lpp ratio is known to yield significant blockage effects, it has no importance for the relative force ratios for the two ships.

The large model was tested in two conditions: With and without bilge keels on the hull. The small model has also been investigated with and without the bilge keels, and furthermore tests with both bilge keels and trip wire were made.

The trip wire is applied to stimulate a turbulent boundary layer on the hull sections outside the bilge keels.

6.3 Test Results

For the small model the following results were obtained:

Froude Number $V/\sqrt{gD}$	Reynolds Number $V \cdot B_m/\nu$	Turbulence Stimulators	Relative Drag Coefficient F_Y/F_C
0.16	$1.04 \cdot 10^5$	Bare hull	1.10
0.12	$7.84 \cdot 10^4$	Bare hull	1.05
0.08	$5.21 \cdot 10^4$	Bare hull	1.19
0.16	$1.04 \cdot 10^5$	Bilge keels	0.94
0.12	$7.84 \cdot 10^4$	Bilge keels	0.93
0.08	$5.21 \cdot 10^4$	Bilge keels	1.05
0.16	$1.04 \cdot 10^5$	Bilge+trip wire	0.94
0.12	$7.84 \cdot 10^4$	Bilge+trip wire	1.00
0.08	$5.21 \cdot 10^4$	Bilge+trip wire	0.95

Table 6.1 Force Ratios for Model Vessel. Scale 1:50.

It is seen that the situation with bilge keels is very similar to the situation with both bilge keels and trip wires, and further that the situation with bare hull deviates significantly from the two other situations. The drag coefficients for the bare hull are greater than for the hull equipped with turbulence stimulation devices.

For the large (1:25) model, the ratio F_Y/F_C was found to equal 1.29 for naked hull as well as for the case with bilge keels fitted. The Froude number was approximately 0.06 and the Reynolds number $1.1 \cdot 10^5$.

The test results are depicted in Fig. 6.3 as function of Froude and Reynolds number.

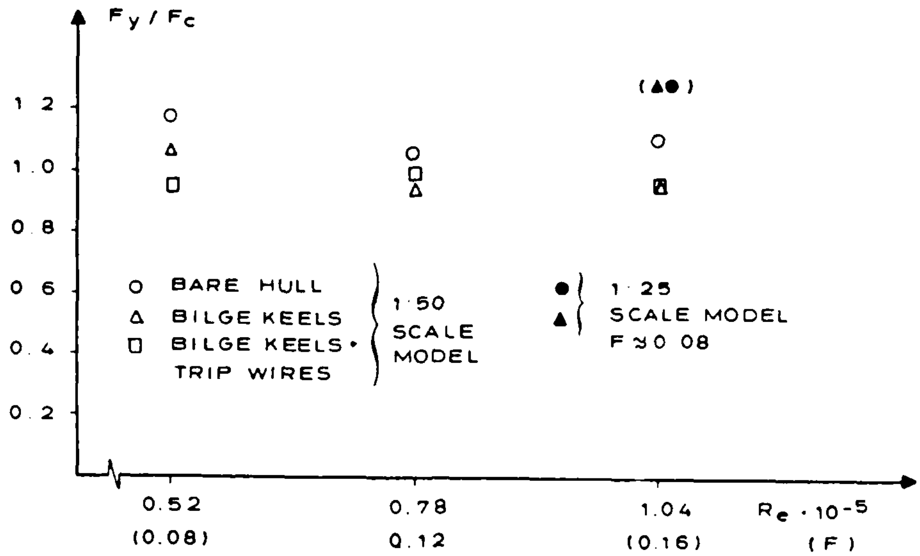


Fig. 6.3 Relative Force Coefficients found in the Model Tests.

6.4 Discussion of Results

The influence of the Reynolds number on the lateral force coefficient has not been reported extensively in the literature. One reason for this is naturally the difficulties inherent in achieving prototype values of the Reynolds number without otherwise disturbing or changing the flow picture. In water tanks limitations to flow speed as well as model size are present. One should also bear in mind that especially for shallow water problems Froude number effects interfere with the phenomenon when large current speeds are applied. Wind tunnel testing puts even more severe restrictions on model size, but larger flow velocity can be achieved and tests applicable for water flows at relatively small Froude numbers can be conducted. It is, however, quite evident that full scale Reynolds numbers cannot be achieved in any of the two types of facilities. The only feasible avenue for obtaining exact values of prototype forces on vessels is to conduct full scale experiments. The problems associated with such experiments are evident, and full scale data are very sparse.

In Ref. /4/ Treshchevsky and Korotkin have reported results of a prototype experiments and comparisons with wind tunnel model tests. Based on information about the influence of roughness on the drag coefficient of circular cylinders, roughness of a certain height was glued to the hull of the model ships and the resulting lateral force coefficients compared remarkably well with the model prototype data as shown in Fig. 6.4 below. The smooth hull model yielded somewhat smaller coefficient values. This may be due to a transition in the boundary layer which occurs on cylinders at Reynolds number of $2 \cdot 10^5$. The details about the experiments are not given in Ref. /4/, e.g. the depth to draft ratio and the value of the Froude number are not given.

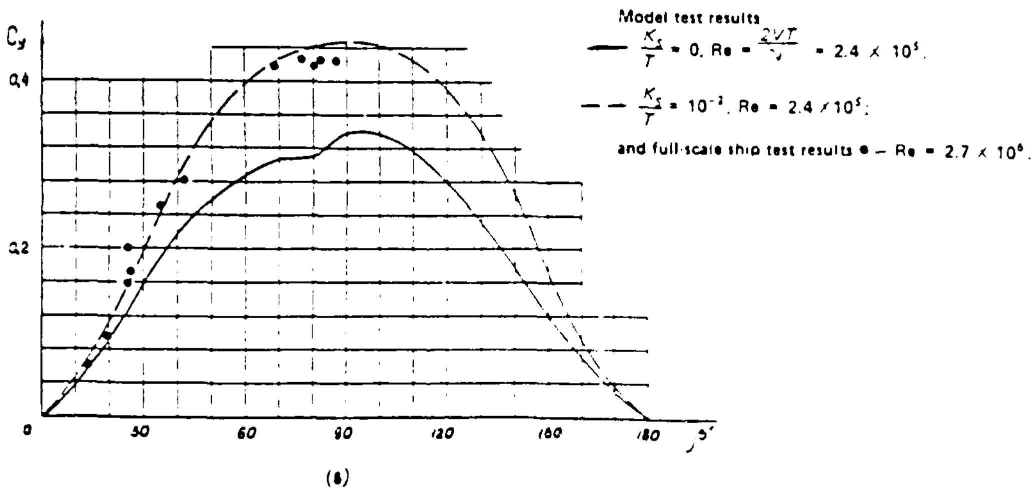


Fig. 6.4 Lateral Force Coefficient on Full Scale Ship and Two Models. From Ref. /4/.

English and Wise, Ref. /5/, have also investigated the influence of turbulence stimulating devices on the lateral drag force on model ships. Instead of distributed roughness they applied trip wires on the model, a method which a recent investigation (see

Ref. /3/) on cylinder drag has shown to be most appropriate in simulating high Reynolds number flow. A decrease of 7% in C_D was found when trip wires were fitted to the naked hull. When bilge keels were added C_D increased by 27%. This increase was followed by changes in the flow picture around the hull caused by the separation zone induced at the bilge keels. Again some details about the test parameters are missing, e.g. Reynolds number value and the depth to draft ratio. The author arrives at the conclusion that scale effects (Re effects) are minimized by applying bilge keels on the model supplemented with trip wires extending from the extremities of the bilge keels to the bow and stern.

As shown previously in Fig. 5.2 the OCIMF, Ref. /1/, has reported C_D-values for various depth/draft ratios for VLCC's based on model tests. Again, details of the tests are not given in Ref. /1/, but it is indicated that the Reynolds numbers in the tests varied between 1.2 and 1.8 times 10^5, and that a decrease in C_D-values was noted with increasing Re number within this interval, and that changes in the flow around the bow and stern were associated with the decrease in C_D-value: Vortex shedding disappeared at the larger Re-numbers. The form of the VLCC's has similarities with (smooth) circular cylinders, and the decrease in C_D may have reasons as for the cylinder case. The magnitude of the decrease is not given, but the resulting C_D-values should be those associated with the largest Re-numbers. By analogy to the circular cylinder this may seem somewhat non-conservative, as vortices are re-established at large Re-numbers, where C_D increases above the value found at critical Re-numbers of 2 to 5 times 10^5.

The NCEL report by Palo and Owens, Ref. /2/, points to an even larger uncertainty with respect to the C_D-values and the influence of Reynold number on these. Fig. 6.5 below from Ref. /2/ shows the C_D-values found from various calculation models and recommendations. The scatter in the C_D-values is significant.

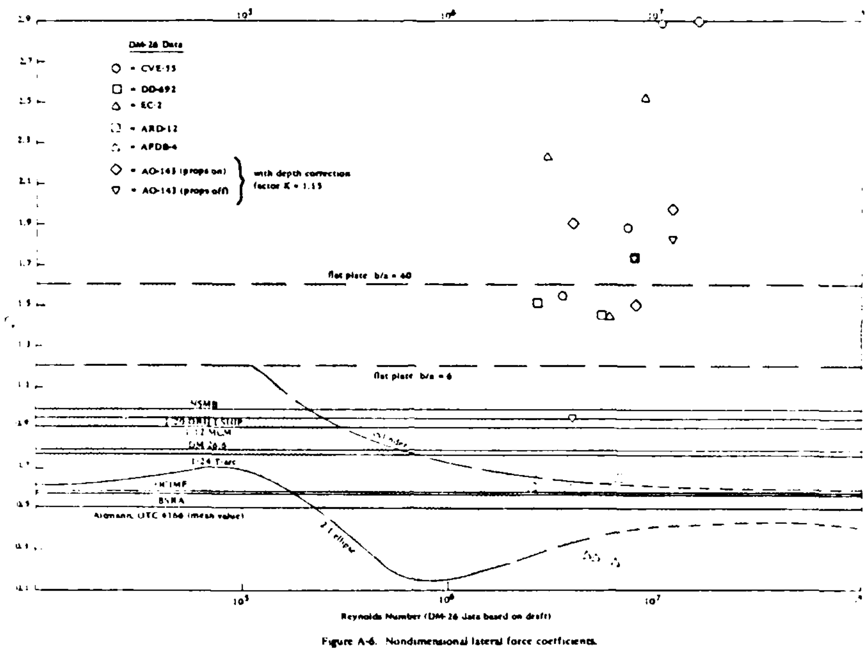


Fig. 6.5 Lateral Drag Forces on Ships in Steady Current. From Ref. /2/.

The data obtained in the present project indicate that the application of bilge keels and trip wires on the hull of the 1:50 scale vessels leads to stable force coefficients for the range of Reynolds and Froude numbers tested. This is in agreement of findings presented in Refs. /4/ and /5/. The reasons for the increase in the lateral force ratio for the 1:25 vessel are not obvious. For the naked hull case the increase is 8% and for bilge keels fitted it is 23%. Compared to the smaller vessel the Reynolds number is more than two times larger, going from 0.5 to 1.1 times 10^5 (Froude number for the 1:25 vessel was somewhat below 0.08, approximately 0.06). There is no reason for an increase in drag coefficient due to the change in Reynolds number. During testing it was observed that the flow was more stable for the 1:25 scale model tests, with less turbulence of the oncoming flow. For circular cylinders turbulence is known to reduce the drag coefficient, when the Reynolds number is below the critical range beginning at 2·

10^5, hence this effect may partly explain the difference found in the present tests. Although it is evident that models with bilge keels (and trip wires) fitted show more stable force coefficients than naked hull models it may be too optimistic to conclude that prototype values of C_D are obtained with these models at much lower Re numbers. However, a more sound basis for drawing conclusions will require either full scale investigations or a more extensive model test programme, presumably conducted in a large wind tunnel. Such tests were beyond the scope for the preliminary and limited investigations reported here. A further discussion of more extensive model tests is included in the second part of this report "Phase II Model Test Programme".

The results obtained indicate that turbulence may have a significant effect on the lateral forces. An even more pronounced effect was obtained by changing the set-up from the one with the model suspended in wires to the one with the ship free to have vertical motions applied for the instability tests. The forces were increased by as much as 40% in the latter set-up. This indicates that due considerations must be given to this effect when designing the prototype mooring arrangements.

7. INSTABILITY TESTS

7.1 Assessment of the Problem

Oscillations of flexible or elastically suspended structures immersed in a moving fluid may either be caused by external fluctuating forces, e.g. due to turbulence in the fluid, or it may be a result of the interaction between the fluid and the structure. For this latter case two types of fluctuating forces may appear. One type which is present even when the structure is kept in fixed position, e.g. vortex shedding from bluff bodies, and another type which is generated due to an initial motion of the body. This latter type of oscillating forces and motions is traditionally referred to as being of the instability type.

Large scale turbulence in natural currents may contain considerable energies at frequencies close to the natural frequency of the vessel motions. An investigation of this phenomenon has not been included in the present project.

For a ship in shallow water exposed to a beam current the two types of forces caused by the fluid-structure interaction may be present and a brief outline of these are given below.

The flow around the ship is sketched in Fig. 7.1. In the regions at the bow and stern vortices are being shed from the hull without flow re-attachment as depicted in Fig. 7.1.a and b. Time varying pressure fields acting on the hull at the bow and stern are related to these pressure fluctuations. If the resulting forces are out of phase a pitch motion may be initiated.

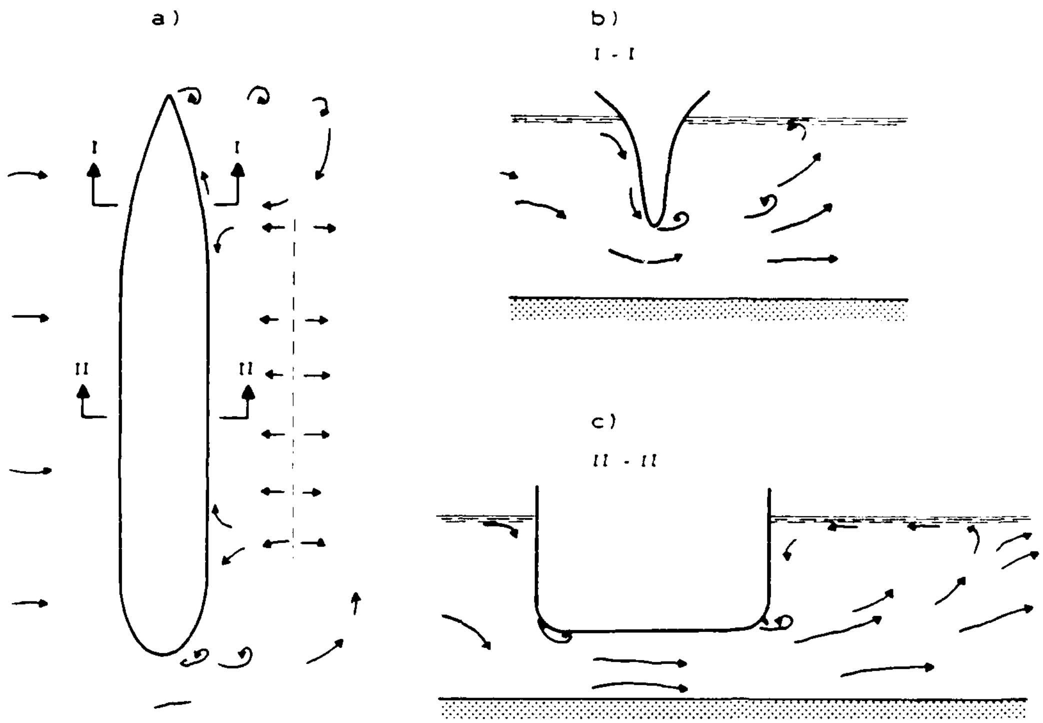


Fig. 7.1 Sketch of the Flow around a Ship exposed to a Beam Current in Shallow Waters.

In the central part of the hull where bilge keels are fitted the flow field is sketched in Fig. 7.1.c. At the upstream water surface a separation zone develops with small return flow velocities. At the upstream bilge keels flow separation occurs, followed by re-attachment and finally flow separation occurs at the downstream bilge keel. Behind the ship a large roller is created with a typical horizontal extension equal to the beam of the ship, meaning that the velocity at the water surface is in the upstream direction, as indicated in Fig. 7.1.a and c.

The pressure field acting on the hull results in a moment which tends to give the ship a mean roll position. If the ship heel is increased (see the sketch in Fig. 7.2) the flow area is decreased at the upstream bilge and increased at the downstream keel. As the flow discharge underneath the ship cannot change instantaneously

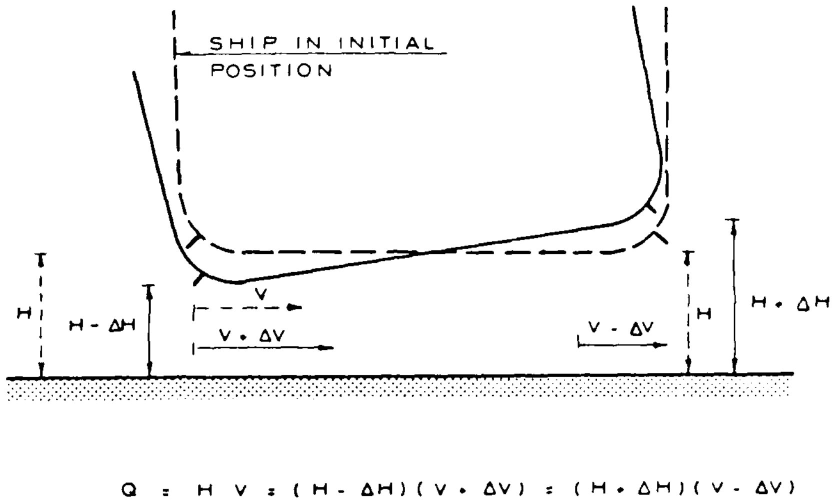


Fig. 7.2 Sketch of the Flow of the Bilge Keel Section and Effect of Roll Motion on Velocity and Pressure Field.

this will result in increased and decreased flow velocities at the up- and downstream keel, respectively, and associated with this is changes in the pressures leading to an amplification of the turning moment in the direction of the roll motion: The mechanism creating a traditional instability type of motion is thus present.

7.2 Model Tests

For these tests the ship was free to have pitch, roll and heave motions whereas the yaw, surge and sway motions were restrained by the rigid rods applied for the mooring. During the tests the ship motions and forces were recorded together with the force on a circular plate yielding a reference force. The measuring system is shown in Fig. 7.3.

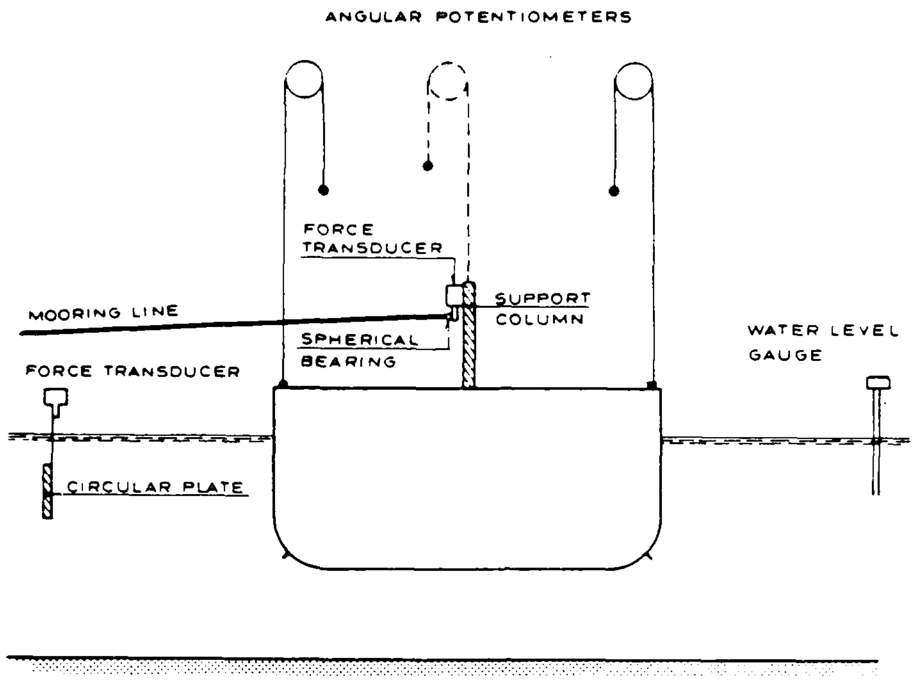


Fig. 7.3 The Measuring System (in principle) applied in the Instability Tests and the Mooring Arrangement.

In addition video recordings were performed showing the motion of the ship.

7.3 Model Test Results

The pitch, roll and heave motions of the model ship were determined from the motion recordings. The resulting values are shown in Dwg. No 1 to 7. Although the test set-up (the mooring lines) differed significantly from the prototype lines, the heave motions have been scaled up to prototype values. It should, however, be stressed that the results of the instability tests only serve to indicate possible motions of the ship, and that neither the amplitudes nor the periods (roll) are to be applied using their exact values.

It is quite evident that a mean roll movement appears for all Froude numbers tested and that this value increased with increasing Froude number. Superimposed on the mean movement is an oscil-

latory roll motion. The double-amplitude of this motion is not significantly influenced by the Froude number.

The heave motion has a similar trend with the Froude number. The mean value increased with increaseing F-values, the amplitudes of the oscillating part are not influenced by the Froude number.

Finally, the pitch motions also appear to have oscillation amplitudes independent of the Froude number.

The motions of the ship have been documented by a video recording.

7.4 Discussion of Results

The tests have revealed that time-varying motions of the moored ship are likely to occur for all flow conditions. The part of the motions, which may be due to vortex shedding is also expected to appear at full scale as vortex shedding is recognized to be present also for very large Reynolds numbers.

Although it was not attempted to prevent one of the possible motions to see the effect on the others, the general impression from the observations made during the testing was, that the roll motion was the one initiating the pitch and the oscillating heave motions. Furthermore, it also seemed that some heeling was necessary to initiate the time-varying roll motion.

Finally, it is important to note that the drag force increased substantially when the vertical restraints on the ship were removed. An increase of 40% in the C_D-value was found for one case.

Besides the apparent consequence for the design of the mooring system this observation also influences the model test programme, which is outlined in the second part of the report.

8. REFERENCES

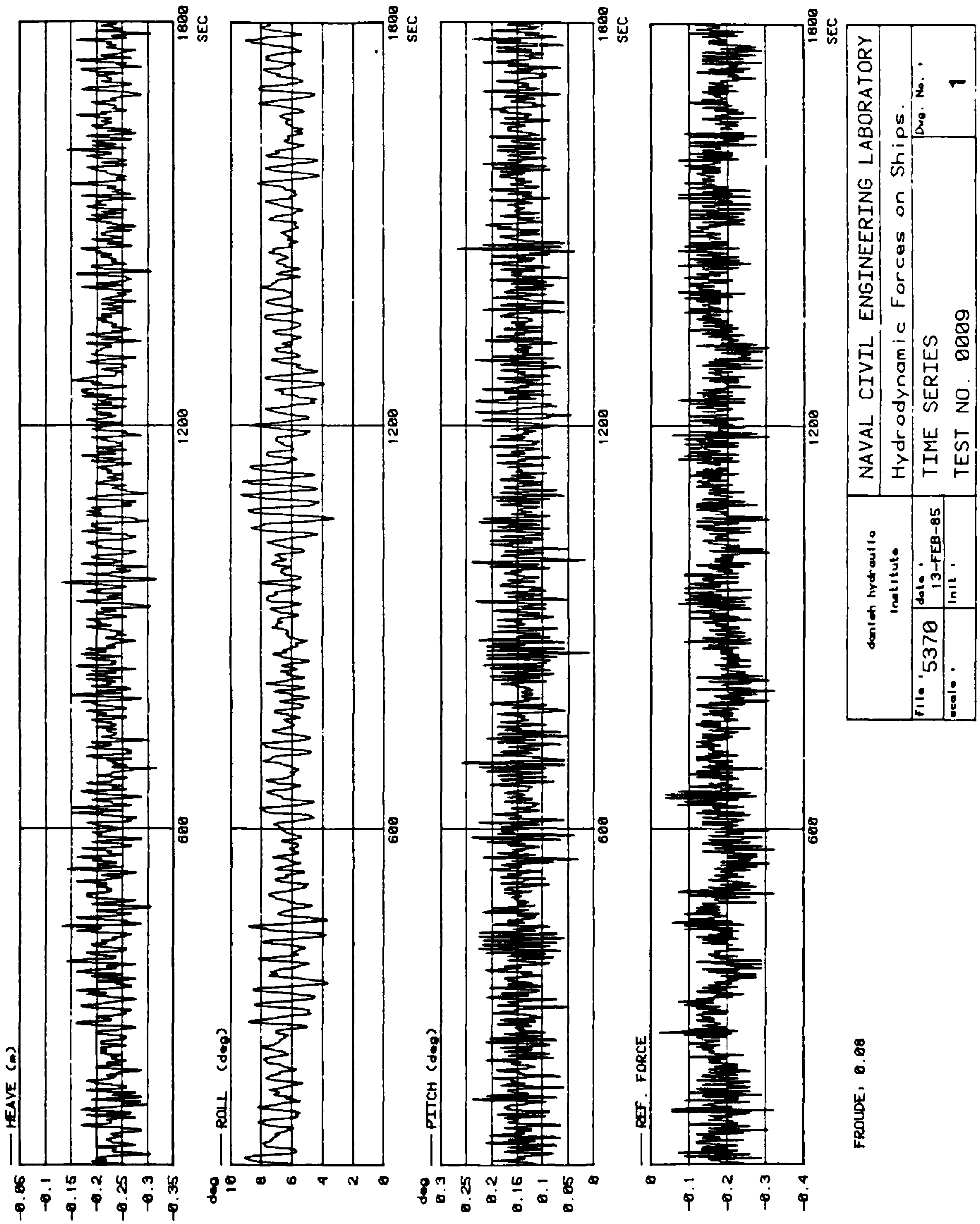
/1/ Oil Companies International Marine Forum (OCIMF), "Prediction of Wind and Current Loads on VLCC's", London 1977.

/2/ NCEL Technical Note No. N-1633, P. Palo and R. Owens, "An Assessment of State-of-the-Art Methods for Calculating Current Loads on Moored Ships", Port Hueneme, 1982.

/3/ Pearcey, H.H., Cash, R.F. and Salter, I.J., "Flow Past Circular Cylinders. Simulation of Full-Scale Flows at Model Scale". Report NMI R 131, OT-R-8208, UK 1982.

/4/ Treshchevsky, V.N. and Korotkin, A.I., "Some Characteristics of Flow Around Ships at Different Drift Angles in Shallow Water". Eleventh Symposium on Naval Hydrodynamics, 1976.

/5/ English, J.W. and Wise, D.A., "Hydrodynamic Aspects of Dynamic Positioning", Transactions, North East Coast Institution of Engineers and Shipbuilders, vol. 92, No. 3m Febr. 1976.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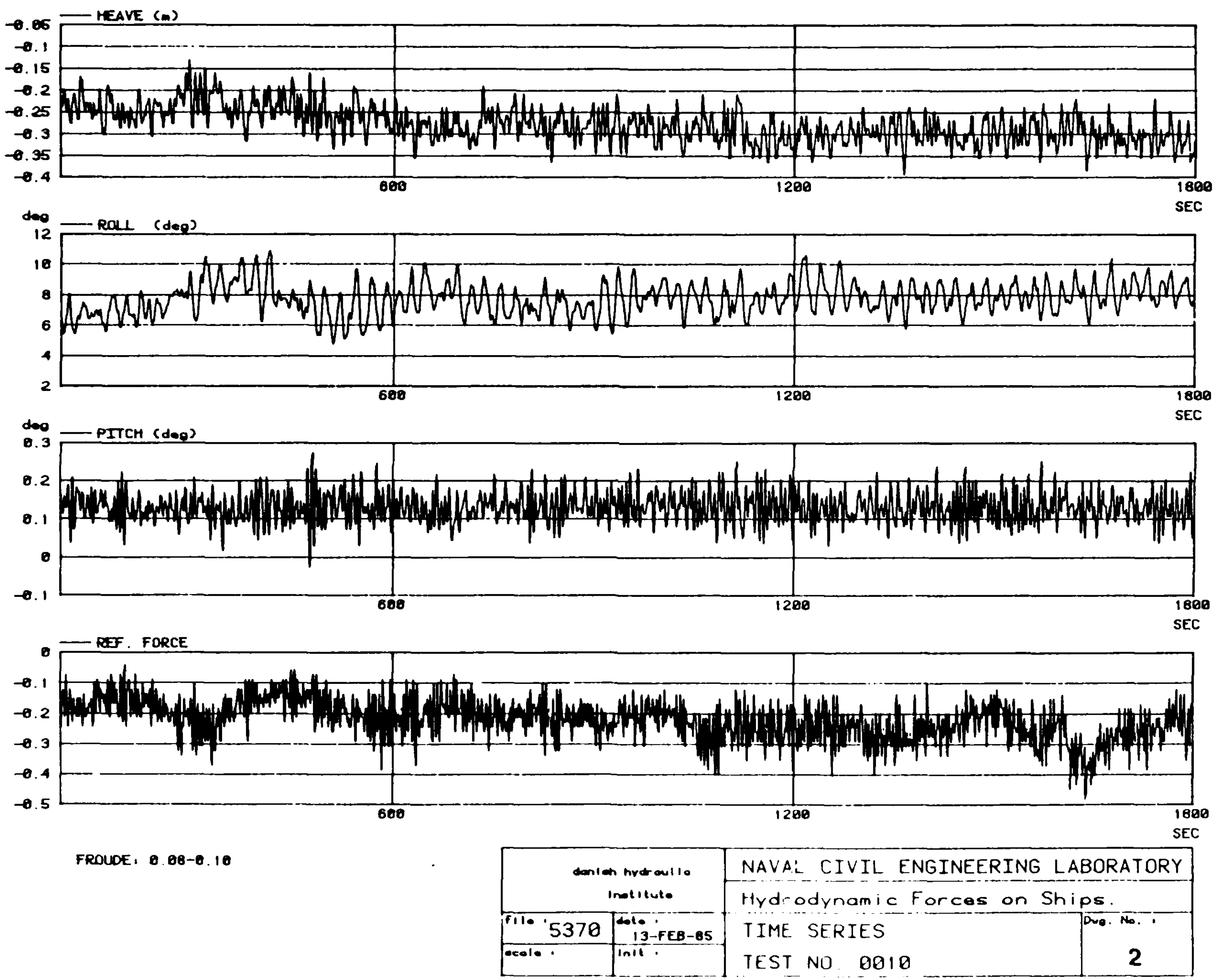
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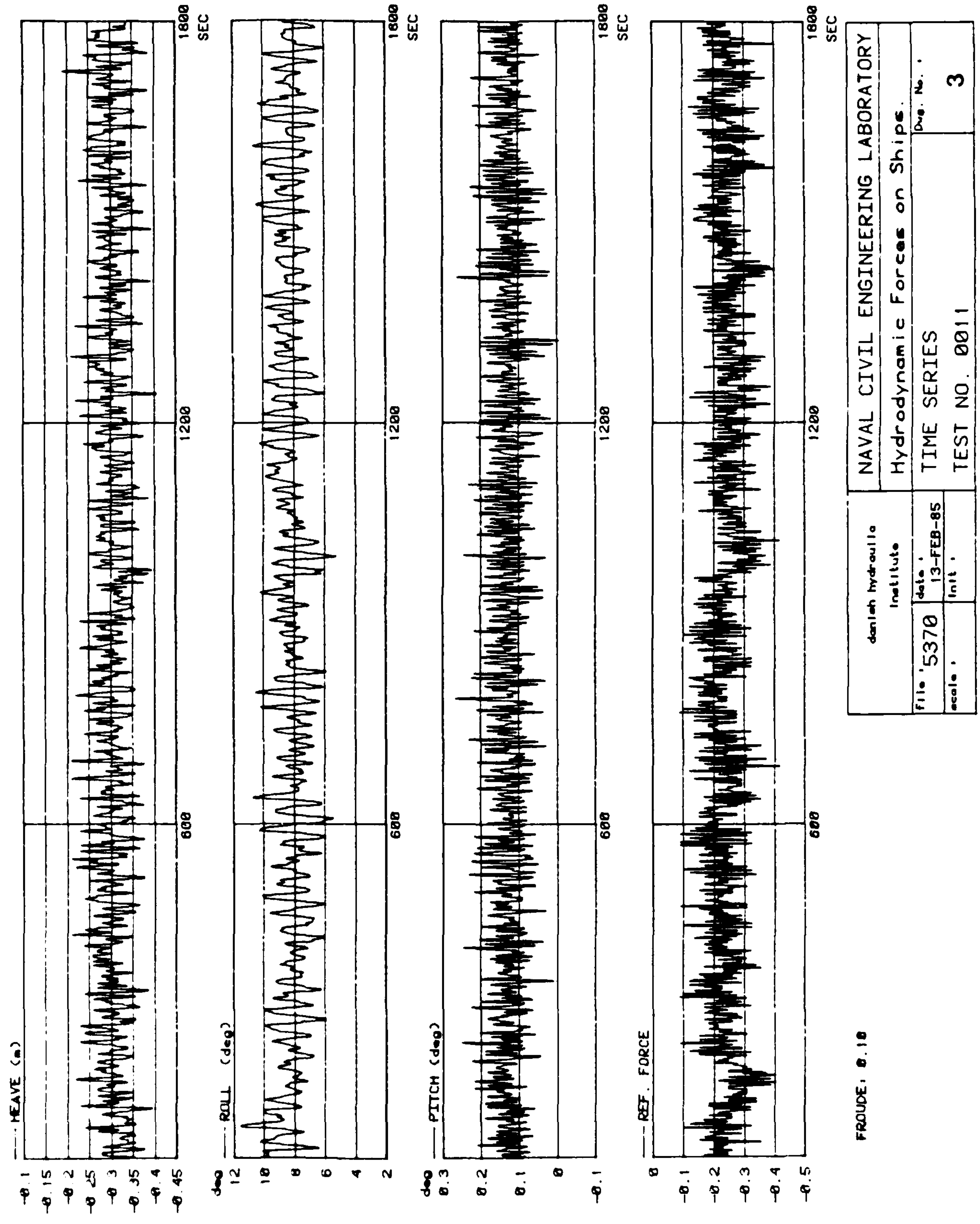
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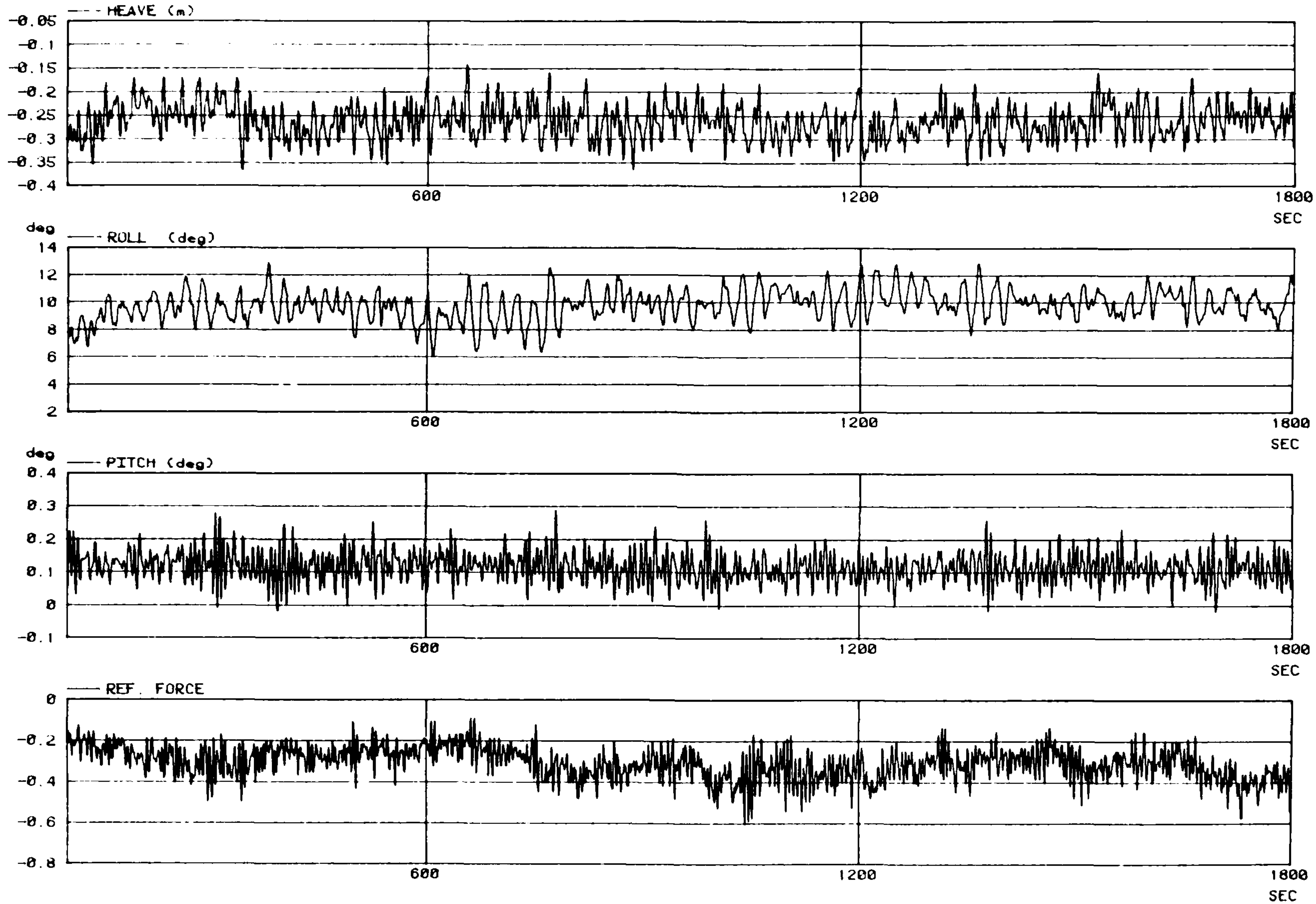

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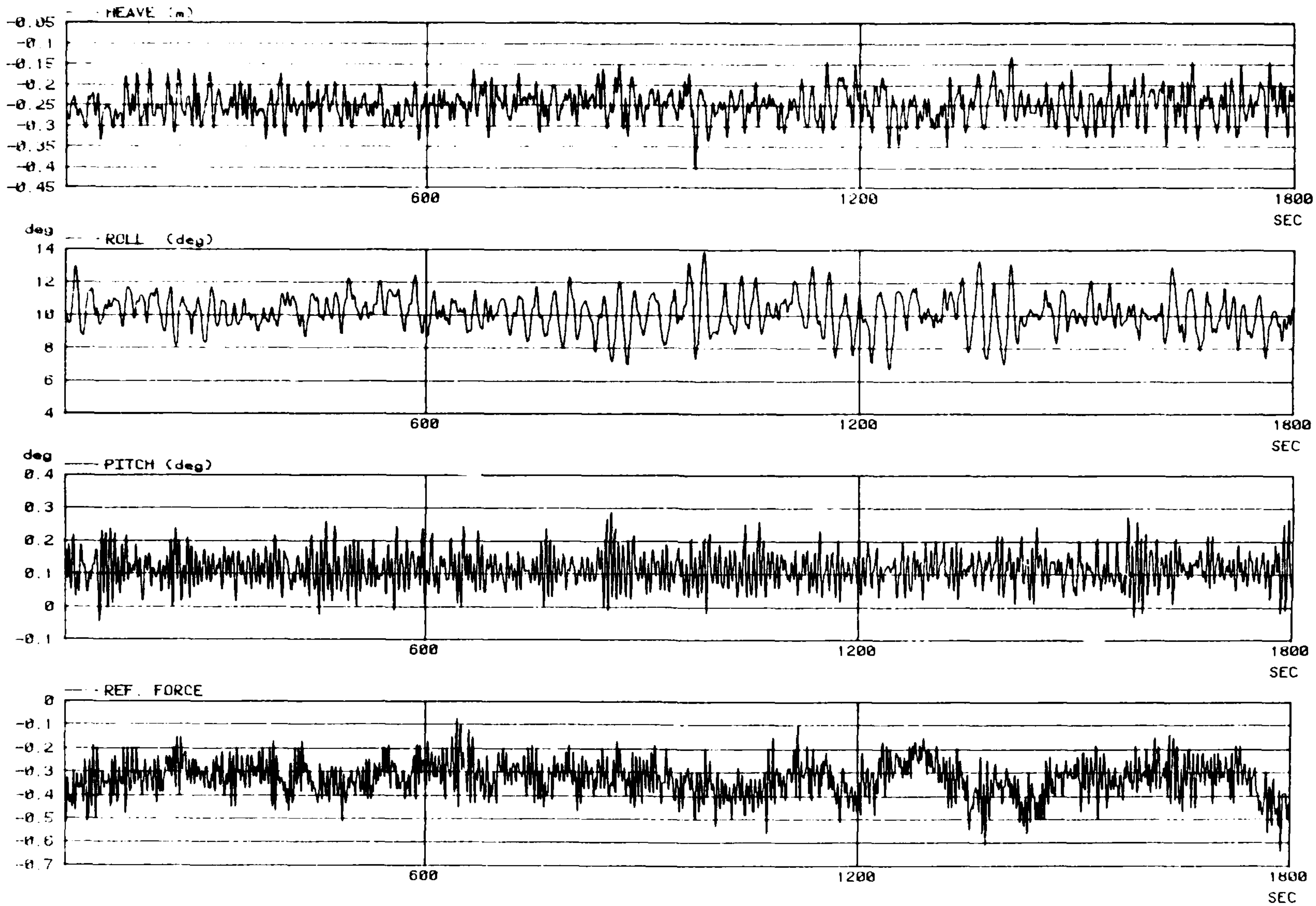

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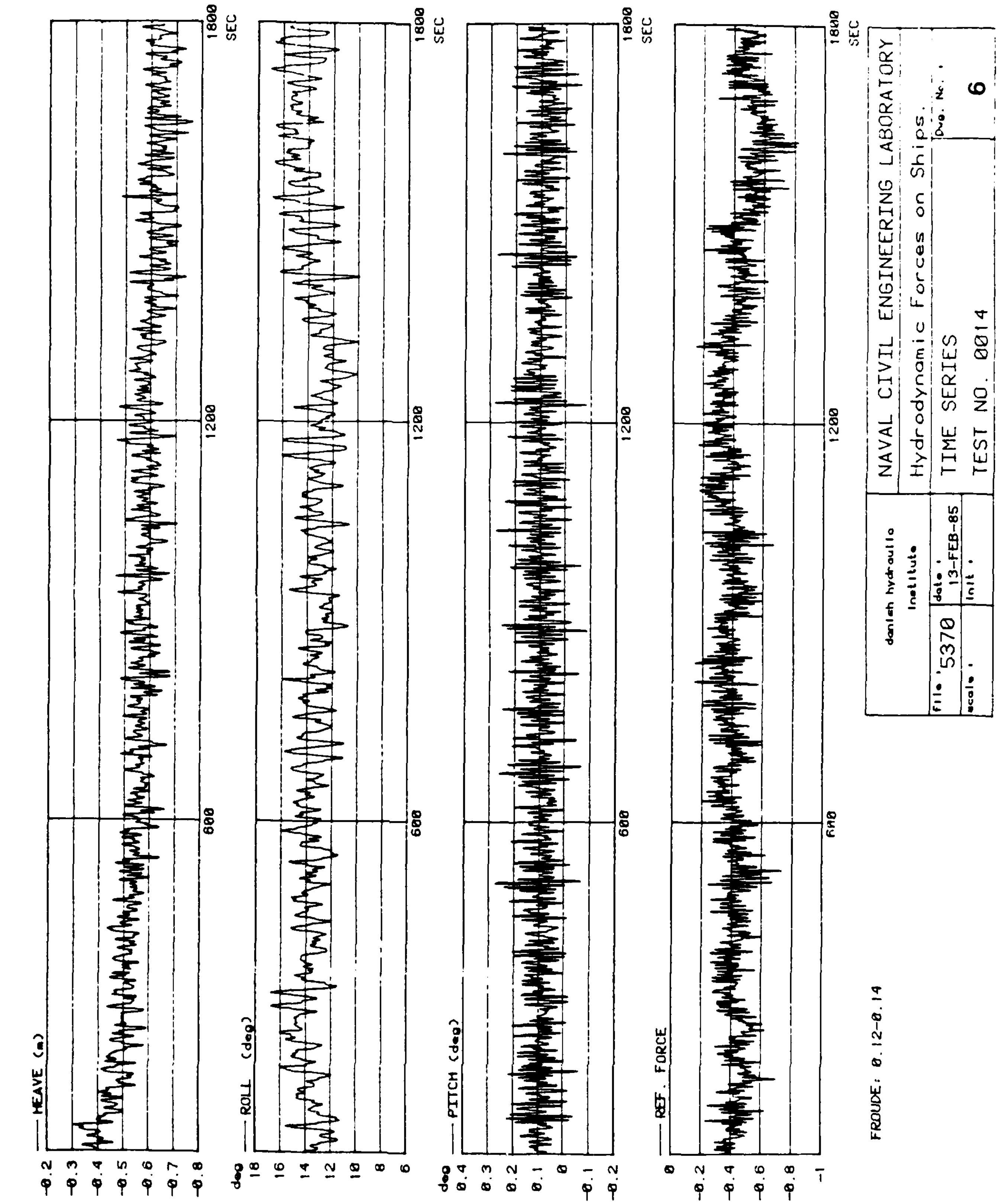
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PITCH (deg)
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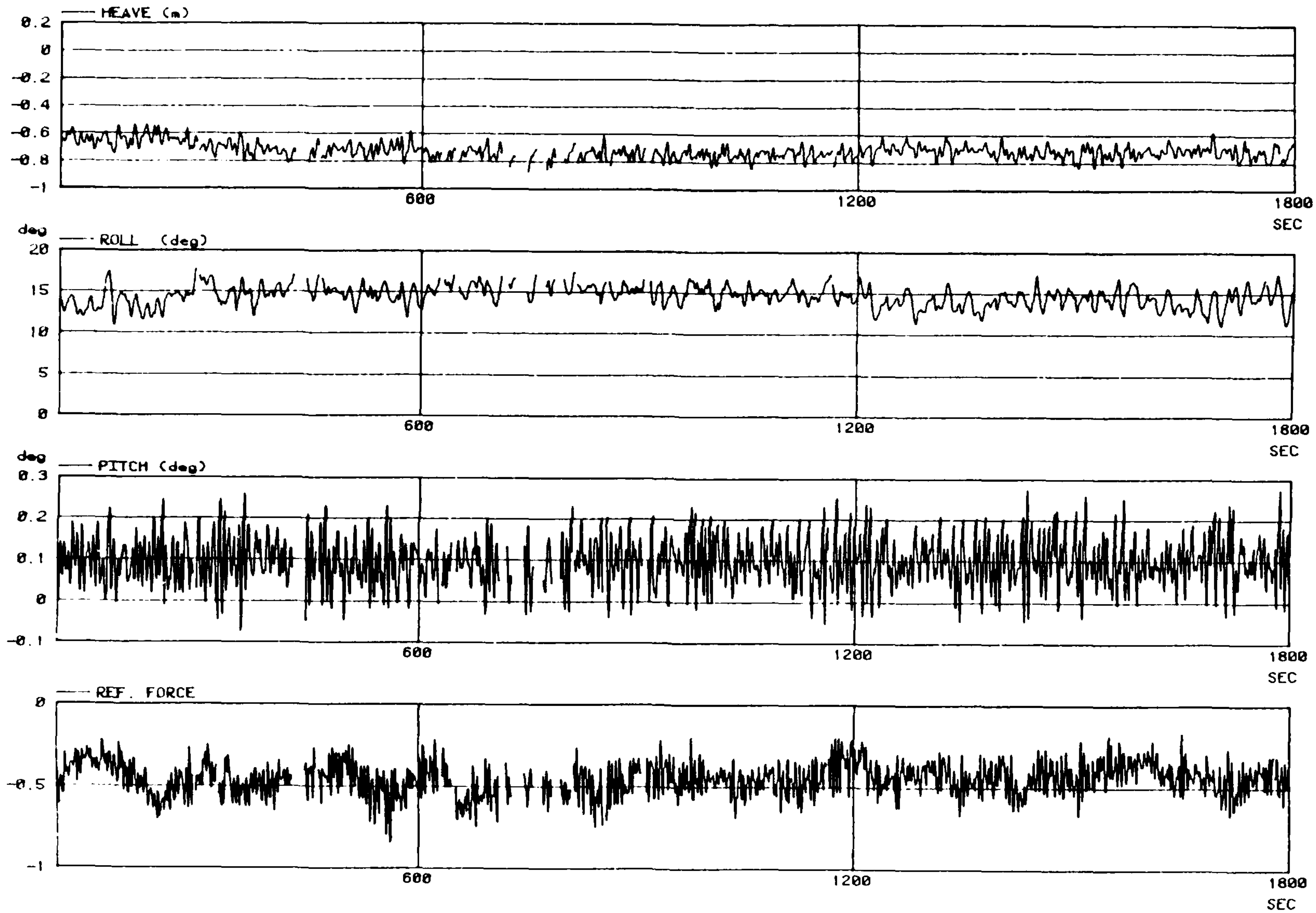

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